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14. ABSTRACT
We collaborated with the Naval Research Laboratory (NRL), Marine Meteorology Division in Monterey, CA to develop novel and efficient data compression techniques for weather data. We developed a differential coding algorithm for lossless compression of radar data by using motion estimation and compensation techniques, with the collateral development of a fast block matching method to improve the computational efficiency of motion estimation schemes. We also improved the compression efficiency of the existing UF file compressor by introducing a new coding method, which exploited the large concentration of blankout markers in the quality-controlled radar data. Furthermore, we studied the feasibility of further compression of the satellite weather images stored in JPEG format. As a result of collaboration with the NRL researchers, the improved and standardized UF radar data file compressor software has been transitioned to testing and installation on ships.

15. SUBJECT TERMS
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Efficient Data Compression Techniques for Weather Data

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OBJECTIVES

The objective of this project is to collaborate with the Naval Research Laboratory, Marine Meteorology Division in Monterey, CA to develop novel and efficient data compression techniques for weather data, with the goal of meeting the challenges of efficiently storing and transmitting ever-increasingly large amounts of weather related data.

APPROACH

A meteorological radar data assimilation system has been developed at the Marine Meteorology Division of the Naval Research Laboratory (NRL) to provide environmental information to enhance the safety of ship and aircraft operations. Radar observations are assimilated into the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) to improve the forecasts of hazardous weather and to provide decision makers with timely products to help exploit or mitigate those predictions. The system will take advantage of a selected group of Navy ships that are to have weather processors installed for their tactical radars (e.g., SPS-48E/G: Hazardous Weather Detection and Display Capability (HWDDC); SPY-1 Tactical Environmental Processor). This group of ships will be able to digitally generate full-resolution, volumetric weather radar data every minute, and also archive them to Universal Format (UF) files. There are plans to transmit three UF files per hour in near-real-time to Fleet Numerical Meteorology and Oceanography Center (FNMOC) where the data assimilation into COAMPS® is conducted.

UF file sizes range from ~5 MB (SPS-48E) to ~13 MB (SPY-1), which would be too large a load on the operational bandwidth of the ships' communication systems. To overcome this obstacle, we have developed a novel UF file compressor that typically reduces UF file sizes by a factor of forty, thus permitting their transmission from a ship to FNMOC.

The current UF file compressor achieved large compression by exploiting only intra-UF file correlations. Since UF files were taken approximately 5 minutes apart, temporal correlations are expected to exist between radar data in neighboring UF files. In this work, we considered differential compression techniques, which aim at efficient UF file transfer over a bandwidth-constrained link in the case where the receiver already has a previous UF file that has been perfectly reconstructed. We employed the block-based motion estimation technique to estimate the temporal correlations between successive UF files. Strictly lossless coding was accomplished by compressing the motion parameters and the residue signals after motion compensation using lossless coding methods. In addition, we introduced a new fast block-matching method for lossless motion estimation in order to significantly reduce the computational complexity of the inter-file compression method.

On the other hand, we attempted to further improve the compression efficiency of the current UF file compressor by modifying the current low-complexity, intra-file compression methods, where thresholding operations were employed to blank out data entries whose values are below certain thresholds and thus considered less critical, as determined by some appropriate quality control requirements. While the current UF file compressor achieved a high efficiency, it did not directly exploit these markers that comprise a significantly large proportion of the data to be compressed. To this end, we proposed a new data compression method, which compresses the blankout markers separately from the critical data entries in the UF data files after thresholding operations.

Besides studying radar data compression algorithms, we also investigated efficient further compression of weather satellite images stored in JPEG format. The satellite images used in the study were downloaded from the NRL, Monterey website for satellite meteorology. The images have already been compressed using the JPEG standard. Further lossy compression of JPEG image in order to reduce the size may result in a poor quality image. Thus, we studied the feasibility of losslessly re-compressing JPEG images without loss of quality. To this end, we tested and compared two open-sourced software packages: one is PackJPG, based on the idea of segmented entropy coding in reference to the EOBs (End-of-Block) of the 8x8 DCT transformed macroblocks. The other is Paq8l, a general-purpose lossless data compressor.

WORK COMPLETED

1. Improvement of the UF file compressor.

By collaborating with Dr. Paul Harasti at NRL, we improved the UF file compressor UFZIP, so that the software could be generalized for all UF file data field identifier variations that have changed in the past between the DoD radars, SPS-48E, SPY-1/TEP and SWR. We also modified the UF file compressor software to determine several parameters (e.g., the maximum ray-record length size) dynamically at run time, rather than specified the values for these parameters statically in the executing script as was previously done.

2. Lossless differential compression of weather radar data using motion estimation and compensation

In order to assess the effectiveness of the inter-file coding approach, we experimented with two methods of extracting the update information between data from two temporally adjacent UF files. (i) Simple subtraction of the reference data from the current data; (ii) A more sophisticated method known as *delta* compressor. We found that neither of these two methods could provide more efficient compression than intra-only compression, which is based on bzip2. Thus we investigated using motion estimation techniques that have been employed by many video data compression standards such as MPEG to capture the temporal correlations between radar data from successive UF files, and to compensate for the ship movement and other motion of weather prior to applying differential coding codes. We analyzed an archived SPS-48E UF data set provided by NRL Monterey. The data were obtained from an at-sea experiment onboard the USS PELELIU (LHA5) in February 2006. This data set contains a wide range of precipitation echoes spanning 22 hours of observations.

3. Computationally efficient block-based motion estimation algorithms using multilevel successive elimination with multiple passes

Block-based motion estimation was found to be effective in capturing the temporal correlations between weather radar data from temporally neighboring UF files. While the exhaustive full search block matching method can find globally optimal motion vectors without any loss in the matching accuracy, high computational complexity of this method limits its practical applications. Lossless block matching algorithms based on successive candidate elimination were found to be effective in reducing the complexity of the full search method. We introduced a new breadth-first method with multiple passes to speed up a well-known fast method called multi-level successive elimination algorithm (MSEA), by exploiting the correlations between matching metrics of different levels.

4. More efficient compression of UF data by exploiting blankout markers due to thresholding operations

We introduced a new UF data compression method, where we divided the thresholded data entries into two categories: blankout markers and critical data entries. We compressed these two types of data entries separately at the encoder. In order to store or transmit the location information of the markers efficiently, we proposed a lossless method based on an approach generally known as DPCM (Differential Pulse Code Modulation), which compresses the location information and perfectly reconstructs the location information. We applied the proposed method on the UF radar data set and compared its compression efficiencies with the original method used by the UF file compressor, which directly compressed the thresholded data without separating the blankout markers from the critical DZ data. We demonstrated that the new method achieved higher compression than the original method.

5. Further compression of weather satellite images in JPEG format

Since the satellite images on the NRL web page have already been compressed using the JPEG standard, we can only reconstruct the images by decoding the downloaded JPEG bitstreams that correspond to the displayed images on the web. The reconstructed images might be a distorted version of the original raw image data, due to the lossy nature of the JPEG technique. In order to assess the feasibility of further compressing the images, we applied PackJPG and Paq8l on the reconstructed images and compare the compressed file sizes with the size of the JPEG bitstreams.

RESULTS

1. Compression of UF data files with the improved and generalized UFZIP software

The UF file compression software UFZIP was improved in terms of compression efficiencies. In addition, it was standardized to extend its applications to the UF data files from other DoD Doppler radars including SWR and TEP. Table 1 shows some test results with SPS-48E, SWR UF and TEP data files.

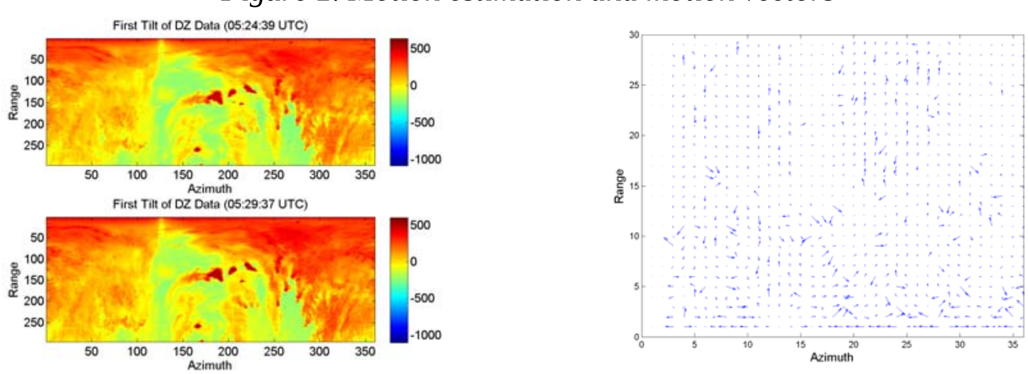
Table 1. Test results of the improved and generalized UFZIP software

UF File Type	**SPS-48E**	**SWR**	**TEP**
Original File Size	5.4 Mb	17.0 Mb	12.1 Mb
File Size After Compression	0.245 Mb	0.34 Mb	0.13 Mb
Size Reduction Ratio	*22:1*	*50:1*	*93:1*

2. Efficient lossless differential compression of weather radar data using motion estimation and compensation

Figure 1 (b) gives an example of motion vectors as a result of motion estimation on data from two temporally neighboring UF files in Figure 1 (a).

Figure 1. Motion estimation and motion vectors

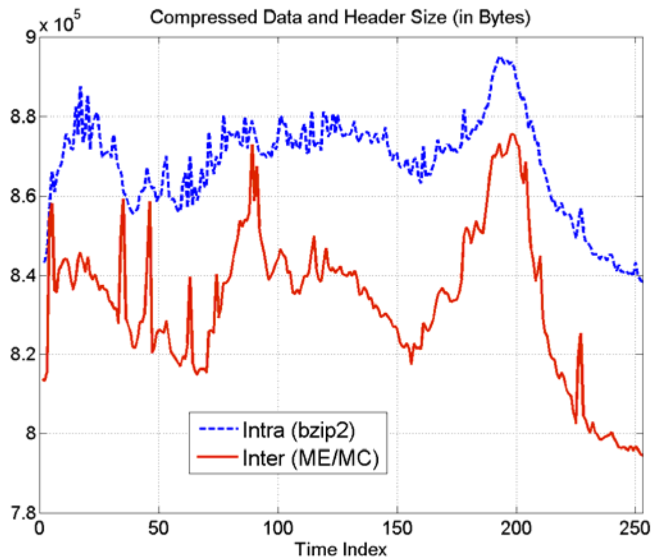


(a) (b)

(a) DZ data from two adjacent UF files. (b) Motion vectors

As can be seen from Figure 2, the inter-file compression method outperforms the intra-file compression method consistently for all the UF files in the dataset, thereby demonstrating the effectiveness of the proposed method based on motion estimation and compensation

Figure 2. Comparison of the sizes of the compressed files between the inter-file compression method based on motion estimation and compensation, and the intra-file compression method based on bzip2.



The proposed inter-file differential compression method is completely lossless and more than meets the 1 MB maximum file size requirement imposed by the operational bandwidth. However, in terms of overall file size reduction, it cannot compete with the existing intra-file data reduction and compression technique used in UFZIP, which is essentially a *lossy* compressor. While providing a useful lossless data compression option for solving the current problem of efficient file transfer, the proposed differential compression technique may also benefit applications in efficient data archiving, where strictly lossless data compression is often a requirement.

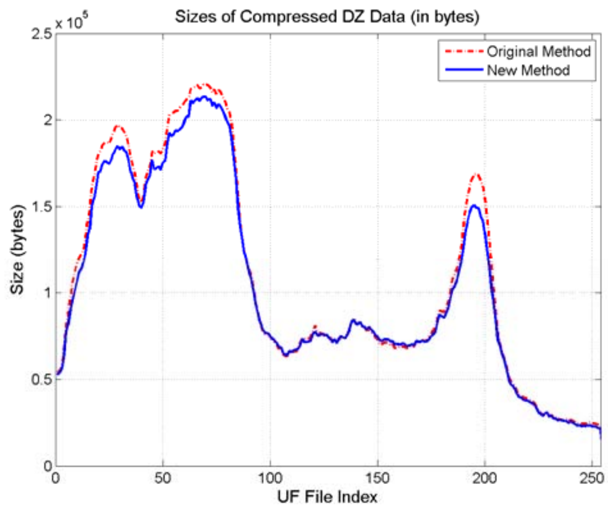
3. Computationally efficient block-based motion estimation algorithm

We proposed a novel multiple-pass method to prioritize the search of different candidate blocks. By exploiting the inherent correlations between matching metrics at different levels, the proposed method was shown to achieve an average speedup of over *17* times over the exhaustive full search method on several benchmark video sequences in CIF format, representing a significant improvement over the conventional MSEA method, which is known for its high computational efficiency for block matching in motion estimation. The proposed fast block-matching method is expected to be able to substantially reduce the computational complexity of the encoder, if it is applied to compression of weather radar data,

4. More efficient compression of UF data by exploiting blankout markers

We applied the a new method of separately coding blankout markers and critical data entries on the UF radar data set, and compared its compression efficiencies with the original method used in UFZIP, which directly compressed the thresholded data without separating the blankout markers from the critical DZ data. As can be seen in Figure 3, on average, the new method achieves an improvement of approximately 3% over the original method for all UF files in the data set, with a maximal improvement of over 13%.

Figure 3. Comparison of the sizes of the compressed DZ data.



5. Further compression of weather satellite images in JPEG format

Table 2 shows some of test results on satellite images taken for each Pacific area.

Table 2. Further compression of satellite images in JPEG format

Image Name	**JPEG (Kb)**	**PackJPG (Kb)**	**Paq8l (Kb)**
20101120.0000.goes11.vis.fd.x.jpg	133	111	112
20101120.0300.goes11.vis.fd.x.jpg	114	94.4	94.5
20101120.1200.goes11.vis.fd.x.jpg	107	87.5	87.4
20101120.1500.goes11.vis.fd.x.jpg	124	103	103
20101120.1800.goes11.vis.fd.x.jpg	148	124	125
20101121.0000.goes11.vis.fd.x.jpg	133	111	112
20101121.0300.goes11.vis.fd.x.jpg	114	94.5	94.7
20101121.1200.goes11.vis.fd.x.jpg	107	87.4	87.4
Total	*980*	*813*	*816*

It can be seen that both PackJPG and Paq81 could achieve a further reduction of the JPEG image sizes by about 17%. In terms of computational efficiency, PackJPG ran faster than Paq81. Similar results were obtained for a large number of satellite images for other regions. Thus, we demonstrated it was feasible to further compress the satellite images stored in JPEG format.

IMPACT/APPLICATIONS

Our attempt to apply motion estimation/compensation methods to address the problem of lossless compression of weather radar data could be the first of its kind, to the best of our knowledge.

NRL has delivered the UF file compressor to Basic Commerce and Industries, Moorestown, NJ, who is the developer of the HWDDC under contract for Space and Naval Warfare Systems Command (SPAWAR) Systems Center, Pacific, San Diego, CA. From May to August 2009, BCI and SPAWAR conducted tests using the land-based SPS-48E at Navy facilities in Dam Neck, VA on the HWDDC. One of these tests was the successful transfer of compressed UF files from the HWDDC to NRL in real-time. In June 2010, SPAWAR Systems Center, Pacific, conducted further tests at their Integration Test Facility using archived and compressed SPS-48E/HWDDC UF files. These tests measured the bandwidth load during the transmission of a series of compressed UF files from a HWDDC to a simulated FNMOC Linux Server. The simulation was conducted continuously over a 24 hour period and successfully met the bandwidth requirements. Having passed all the required tests, the HWDDC has since been installed on the USS Boxer (LHD-4) and the USS Reagan (CVN-76), and ten more ships are scheduled for installations by October 2012.

TRANSITIONS

As a result of the collaboration with NRL researchers, UFZIP/ UFUNZIP (Version 1.0): UF files Compression and Decompression Software Package, was transitioned to SPAWAR/HWDDC, on 19 June 2009.

PUBLICATIONS

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Proc. of the 35th International Conference on Acoustics, Speech, and Signal Processing (ICASSP'10), Dallas, TX, March 2010.

3. W. D. Pan, P. R. Harasti, M. Frost, Q. Zhao, J. Cook, T. Maese, and L. J. Wagner, "Lossless differential compression of weather radar data in universal format using motion estimation and compensation," in Proc. of AMS 26th Conference on International Interactive Information and Processing Systems (IIPS'10) for Meteorology, Oceanography, and Hydrology, Atlanta, Georgia, January 2010.

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